DYNAMICS OF GROOVE FORMATION ON PHOBOS BY EJECTA FROM STICKNEY.

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We consider the origin of a subset of the grooves on Phobos which appear to be associated with the impact crater Stickney, assuming that these grooves were formed by ejecta clasts with diameters of order 100 m which left Stickney at velocities such that they were able to slide, roll or bounce to distances of order one quarter the circumference of Phobos, partly crushing the regolith and partly pushing it aside as they moved. We show that this mechanism is physically possible and that it is consistent with the sizes, shapes and lengths of the grooves for plausible values of the material properties of both the regolith and the ejecta clasts. Because the escape velocity from Phobos varies by more than a factor of two over the surface of the satellite, it is possible for these clasts to leave the surface again after generating grooves.

Primary crater ejecta on Phobos

The materials forming ejecta deposits on Phobos will be largely those which would have remained in the crater rim unit on the Earth and Moon (1), since most of the material ejected from the transient crater cavity has at least the escape velocity from Phobos and much of it has the escape velocity from the Phobos-Mars system. The local escape velocity from the surface of Phobos varies from about 3 to 8 m/s, depending on the position on the surface and the direction of launch (2, 3). We treat separately the vertical and horizontal forces acting on clasts launched at speeds just below the local escape speed at elevation angles close to zero.

Groove depth and width

Using a standard result from soil mechanics, if a spherical clast, radius r and density d_b, sinks by an amount D_f into a regolith of density d_r and cohesive strength C to produce a contact area πR_f^2, then

$$(4/3)\ \pi\ r^3\ d_b\ g\ =\ (\pi\ R_f^2)\ (1.3\ N_c\ C + d_r\ g\ [N_q\ D_f + 0.6\ N_g\ R_f])$$

where g is the gravity, and N_c, N_q and N_g are dimensionless constants with values close to 30, 18 and 17, respectively, for a loosely compacted regolith with an internal friction angle of 38^o. If $R_f = f\ r$ and $D_f = q\ r$, so that $f^2 = 2\ q - q^2$, and we work in terms of the easily measured aspect ratio a, where $a = D_f / (2\ R_f)$, for which $q = 4\ a^2/(1 + 2\ a^2)$, then

$$C\ =\ ([r\ g]/39)\ (\ [4 / 3\ f^2]\ d_b\ -\ [18\ q\ +\ 10.2\ f]\ d_r\ )$$

in which C is effectively given as a function of a. We take d_b = 2000 kg/m^3, close to the bulk density of Phobos, and use values of d_r = 800, 1000 and 1200 kg/m^3, based on the assumption that the regolith density will be somewhat less on Phobos than on the Moon. For each value of d_r there is a limiting value of a above which the implied value of C is negative. This implies that, even if the regolith is strengthless, the boulder does not have a great enough weight to form a depression with a value of a greater than the limiting value. The observed range of groove depth to width ratios (0.1 to 0.15: ref. 4) is consistent with values of C in the range 300 to 10 Pa. The upper part of this range overlaps with that found for lunar regolith cohesive strengths (1000 to 100 Pa) and the comparison implies that regolith strengths on Phobos are typically about a factor of 10 less than on the Moon. The upper limiting values of a range from ~0.145 for d_r = 1200 kg/m^3 to 0.167 for d_r = 800 kg/m^3. For values of a in the range 0.1 (the observed approximate lower limit) to 0.167 (the theoretical upper limit for the range of material properties used here), the radii of the ejecta clasts required to produce grooves with widths of 100 m then lie in the range ~140 to ~83 m.

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Energetics of ejecta clast motion

We analyse lateral ejecta clast motion using equations (5) describing the forces acting on the surface sampler arms of the Viking lander spacecraft. These equations describe the horizontal and vertical forces generated on a blade of prescribed shape moving horizontally at a given velocity through the upper part of a regolith layer, and deal with two extreme circumstances in which pure friction or pure cohesion constrain the motion. When we replace the horizontal and vertical blade dimensions with $2R_f$ and D_f, respectively, in the equations for the horizontal forces, and substitute appropriate values of $q = 0.1$, $f = 0.19$ (for which $a = 0.162$, near the upper end of the likely range found in the previous section), we find that both equations take the form $- (4/3) \pi r^3 d_b\ u\ (du/dx) = Q\, d_r\, g\, r^3 \{ S + T [u^2/(g\, r)] \}$

where [$Q = 0.008299$; $S = 4.15$; $T = 12.6$, pure friction case], [$Q = 0.006387$; $S = 17.35[C/(d_r\, g\, r)]^{1.21}$; $T = 6.4$, pure cohesion]. If there were no other considerations, we could integrate this equation from an initial velocity u_i to find the variation of u with distance x and so find the range X at which u was zero. However, Stickney is located very close to one of the two local topographic high spots on the roughly triaxial ellipsoidal body of Phobos. The apparent surface gravity on Phobos (3) has its minima of 2.9 mm/s^2 at the topographic highs and increases towards the topographic lows, reaching 5.2 mm/s^2 at the leading and trailing points and 5.8 mm/s^2 at the poles. Thus, any clast moving along the surface away from Stickney must travel down a gradient relative to the local radius vectors and gain energy from the gravitational field. Integrating the above equation, the velocity variation is found to be

$$u_2^2 = 2\, g\, DZ + \frac{S\, g\, r + T u_1^2}{T} \exp\left\{ - DX \frac{3\, Q\, T\, d_r}{2 \pi\, r\, d_b} \right\} - \frac{S\, g\, r}{T}$$

where the clast changes its velocity from u_1 to u_2 while moving a lateral distance DX and changing its distance from the center of Phobos by an amount DZ. The relation between DX and DZ is specified numerically from the observed shape of Phobos. We find that, for some combinations of clast size and initial velocity the speed decreases monotonically with distance from the rim; however, for many other combinations there is a range of travel distances over which the conversion of potential to kinetic energy more than compensates for the energy used in redistributing the regolith, and a significant increase in the speed occurs before the energy loss processes eventually dominate and the clast comes to rest. Dobrovolskis and Burns (3) calculated the trajectories of ejecta clasts launched from various points on the surface of Phobos into its equatorial plane for a wide range of speeds and two different elevation angles, 45^o and 60^o. Unfortunately, they do not provide examples for near-zero elevation angles, so we cannot follow through in extreme detail the significance of the speed variations we calculate. However, they show that the local escape speed for the higher elevation angles increases slowly to the East from Stickney for ejecta travelling eastwards and decreases quite quickly to the West from Stickney for ejecta travelling westwards. Given the significant uncertainties in many of the parameters used in the velocity calculations, and the fact that the actual topography of Phobos differs considerably from that of a triaxial ellipsoid, we consider that it is entirely possible for an ejecta clast to fail to escape when it is first ejected from Stickney, but to escape at some later point along its path across the surface.

References.

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